Nuclear Criticality Safety Engineering Training
Module 12 [1]

PREPARATION OF NUCLEAR CRITICALITY SAFETY EVALUATIONS

LESSON OBJECTIVE:

To introduce the elements of a nuclear criticality safety evaluation (NCSE) and the underlying thought processes that contribute to the development of a good NCSE.

Introduction

This module is intended to help the inexperienced criticality safety professional (CSP) understand the thought processes that go into preparing a nuclear criticality safety evaluation (NCSE), and perhaps remind the experienced person about the principles that have become automatic over time. While the format and content of the NCSE are often given in Standards or Guides, little is said about the underlying approach and the target objectives used to develop a good NCSE. This module is an attempt to fill that gap, and might be subtitled *The Philosophy of Preparing NCSEs*. The approach taken in this module might be compared to that of a primer. The module makes extensive use of an example NCSE that might have been written for a hypothetical facility. As you read each section of this NCSET module, refer to the sections of the sample NCSE that is included in its entirely following the module.

What is a good criticality safety evaluation?

The ultimate product of a criticality safety evaluation is a document that prescribes the criticality safety controls and limits for an operation with fissionable material such that the operation is criticality safe under all normal and credible abnormal conditions. A good NCSE takes the reader through the process that leads to those limits and controls, explains the basis for all assumptions and conclusions and supports the conclusions with appropriate validated calculations or references.

Basic steps in the development of a NCSE

Any group of CSPs would undoubtedly disagree when asked to list the steps to follow in the development of a NCSE. However, the following objectives should be met by any approach used to develop a NCSE.

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[1]Developed for the U. S. Department of Energy Nuclear Criticality Safety Program by James A. Morman, Argonne National Laboratory, and the DOE Criticality Safety Support Group.

1. Know the system/facilty being analyzed.
   Thorough and accurate knowledge is a prerequisite to a good analysis.
2. Identify potential criticality accident scenarios.
   This can be done using formal methods (e.g., failure modes and effects analysis, event tree analysis) or by using engineering judgment based on operating experience, incident data and interviews with operations personnel. Adherence to the double contingency principle should be demonstrated except in rare circumstances such as shielded facilities.
3. Eliminate potential accident scenarios whenever practical.
   Modify the facility, equipment or processes to eliminate initiating events to the extent possible.
4. Use the preferred hierarchy of criticality safety controls.
   The preferred order of controls is: passive engineered controls, active engineered controls, administrative controls. Ensure that the complete control set is achievable and fits within the total safety program.
5. Document the nuclear criticality safety basis.
   Documentation should include the safety basis, the analyses, and the derivation of controls and the derivation of controls and limits.

The following list is a reasonable set of steps that meets the above objectives, but others could serve as well, provided the final product contains the same information as the one developed according to this outline.

1. Familiarization with operations and the facility
2. Description of methodology
3. Identification of contingencies that could affect NCS
4. Analysis of normal operations and contingencies
5. Derivation of controls and operating limits
6. Preparation of the CSE document

These steps are obviously not independent and often overlap as the NCSE is being developed. For example, analysis of normal operations and contingencies usually is done at the same time. Development of limits is a part of the analysis. Although some people might approach the NCSE elements in a different order, Step 1 must always be done first. As each step in the NCSE process is discussed, the sample NCSE will be used to demonstrate that step.

1. Familiarization with Operations and the Facility

It should be obvious that the CSP must understand the operations that will be analyzed in the NCSE, but very often the novice will rely on operations personnel to describe the key points of the operations. Many times the CSP will rely on the same operations people to identify potential abnormal and accident conditions. This can be a good starting point, but the CSP must have a first-hand understanding of the facility, operations and processes, do his own analysis, and then discuss the results with operations personnel. Ongoing interactions with the operations staff and the operators are a necessary part of performing a NCSE.

How does one go about learning this background information? In today's safety climate, every process and operation requires safety reviews, system design descriptions, operating procedures, etc. Every non-reactor nuclear facility has some form of an approved Safety Analysis Report (SAR) or Documented Safety Analysis (DSA). The SAR provides basic information about the facility including dimensions, proximity of the other laboratories, utilities entering the laboratory, etc. It also discusses hazards in other parts of the building that could impact operations in the subject area. Combined with the educational and background training of the CSP, much of the information needed to start the process can be extracted from these documents.

Most, if not all, operations have procedures associated with them and new experiments usually have review packages that have been approved by safety committees. Experiment plans generally provide technical drawings, lists of connections to utilities and enough information to supplement the safety basis documents as a starting point for discussions during the facility walk-through. Read and understand all the background material that can be found.

Read Section 1 of the Sample NCSE

The next step in understanding the operations and the facility should be a walk-through with scientific staff, operators and technicians. This interaction lets the CSP visually see the layout of the facility and ask detailed questions about the equipment and operations. Ask questions of the operations staff, facility staff and the operators who are the first line of safety when handling fissionable materials. These people can provide insights into problem areas, potential accidents and operating conditions that the CSP may not notice. It usually takes more than one visit to understand the process and equipment well enough to develop the NCSE.

Another sometimes-overlooked point is the rest of the facility in which the operation is taking place. The CSP should understand how this operation interacts, or could interact, with other operations in the facility or nearby facilities. Similarly, operations in nearby facilities should be examined for potential impacts on the subject operation.

It is extremely important that the CSP preparing the NCSE understand every operation that will be performed in the facility using fissile material. At times this might require consulting experts in other fields, such as chemistry, when process changes could result in potential criticality safety problems, such as solids precipitating from solutions. The NCSE should describe all of the operations or types of operations covered by the analysis along with these potential problems.

Read Section 2 of the Sample NCSE

2. Description of Methodology

It is generally best to start with simple analysis techniques, such as handbook values, and work up to detailed calculational models if needed. In the following example, the KENO-Va code is used, but any validated code is acceptable.

When codes are used to derive limits and controls, they must be *validated*. The purpose of problem-specific code validation is to ensure that the code, cross sections and approach being used are applicable to the system being analyzed. Generally this is accomplished by using the selected code and cross sections to calculate benchmark problems having the same or similar materials and characteristics as the system being analyzed. If no such benchmark cases exist, it is often possible to interpolate or extrapolate to that system. Extrapolation must be done with care and be guided by the experienced criticality safety expert. Recently, the AROBCAD (Applicable Ranges of Bounding Curves and Data) tools developed under the DOE Nuclear Criticality Safety Program have been made available to help determine the applicability of benchmark problems. These tools can be used to provide a quantitative estimate of the suitability of benchmark problems to validate the system being analyzed.

Read Section 4 of the Sample NCSE

3. Identification of Contingencies

During the facility walk-through, the CSP should always be thinking about potential criticality safety problems. All of the factors that affect reactivity should always be kept in mind when looking at the facility. For example, are there external sources of unwanted moderators or reflectors? Are there geometrically unfavorable containers present where materials could inadvertently accumulate? The CSP should be looking for conditions that could occur during normal operations and also off-normal situations such as fire sprinkler activation, water pipe breaks, etc.

By now the CSP should have a reasonably good idea of the operating parameters. What departure from normal operations could lead to a contingency situation? Would it be possible to increase reflection beyond that assumed in the analysis? Can enough moderator be introduced to cause a problem? What happens if the mass limit for the glove box is exceeded by a reasonable amount? Basically, the question is what happens if any control or limit is violated and what can you do to minimize the probability that a violation will occur. Often the contingency analysis will result in changes to the normal operating parameters for either the facility or a process, causing the contingency analysis to be repeated.

Read Section 5 of the Sample NCSE

4. Analysis of Normal Operations and Contingencies

While experiment plans and system design descriptions are good sources of what the normal operations are expected to encompass, it is always necessary to talk to the operators or experimenters. Most of the times these people will want to use as much material as possible in as many different ways as possible, and often they have a different interpretation of what limits the documents actually impose. It is up to the CSP to reconcile what the operators or experimenters want to do with what is criticality safe. Normally, some of the contingency analysis is done at the same time that normal operations are analyzed, since operational limits will sometimes have to be modified based on the contingency analysis results.

Unless a strong case can be made for not adhering to it (e.g., in shielded facilities), the double contingency principle should always be followed during the analyses. As stated in ANSI/ANS-8.1-1998,

> "Process designs should incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions before a criticality accident is possible."

Calculations are needed when standard references and handbooks do not address either the materials or configurations that are expected in the operation for which the NCSE is being prepared. This raises the complexity of the NCSE since the calculational method must be validated. In the sample NCSE, the analysis begins with an evaluation of the minimum critical mass of the materials involved in the operations, then goes on to analyze the specific operations. If standard materials were being used, this first step would not be necessary. However, every NCSE must cover each of the operations that will be done in the facility and credible contingency scenarios taking into account all materials that are expected to be present.

Read Section 6 of the Sample NCSE

Clearly, the sample NCSE evaluated normal operations and contingency situations at the same time. Some CSPs prefer to separate the two sections of the document. Either approach can work as long as all situations are analyzed.

5. Controls and Operating Limits

The NCSE should include a concise summary of all limits and controls that have resulted from the evaluation. While the NCSE might have included references to good practices or defense in depth measures, the controls should reflect only the administrative rules, equipment or systems that are required to maintain the margins to criticality as analyzed in the NCSE, or to ensure that operations are consistent with the assumptions made in the analyses.

6. The NCSE Document

The NCSE document is the product that conveys the results of the criticality safety evaluation to many different types of readers. The document should contain enough detail so that a technical peer review of the NCSE can be done. It should clearly state any assumptions that were made about the presence of criticality control equipment or systems so that safety analysis personnel can evaluate the need for changes or additions to the authorization basis documents. A sampling of the computer code inputs used in the analysis should be included. However, even with the required details in the document, the NCSE must be understandable to high level reviewers, including regulatory oversight groups.

The attached NCSE is based on a preliminary analysis that was done for a small laboratory, but represents a general approach that can be used for most analyses. A key point for the CSP to remember is that not all NCSEs are identical, and that a graded approach is usually necessary based on the materials and hazards at specific facilities.

Read the Remaining Sections of the Sample NCSE

PRELIMINARY
NUCLEAR CRITICALITY SAFETY EVALUATION
FOR BUILDING X OPERATIONS
WITH U(20) MATERIALS

1.0 INTRODUCTION

Building X is a multi-purpose laboratory and office building with several wings branching in both directions from a long central corridor. One wing, Wing B, holds typical radiochemistry laboratories where small amounts of fissile material are used (up to 225 g ^{239}Pu-FGE per laboratory). Another wing, Wing C, has several shielded cells that have the same fissile mass limit, and a third wing, Wing A, physically separated from the other two, is where a new experiment is planned. No other parts of the building use fissile materials. In one laboratory in this wing, Room A-1, experiments related to uranium pyroprocessing have been conducted with depleted uranium for many years. The scientists would like to start using 20% enriched uranium in an inert-atmosphere glove box that contains a high-temperature, water-cooled electrorefiner and a furnace.

The scientists want to bring a quantity of 20% enriched uranium, U(20), in the form of various sized pieces of U_3Si or U_3Si-Al that could be as small as machined fines, dissolve this material in the molten salt electrorefiner, then consolidate the refined uranium product. They would like to have a batch size of about 10 kg of uranium. At this point in time several parameters of the operations are not finalized (such as the molten salt composition, crucible material and transfer containers). Reasonable approximations were used to deduce preliminary conclusions about the criticality safety of the operations and to help establish mass limits for the operations.

2.0 DESCRIPTION OF FACILITIES AND OPERATIONS

2.1 Facility Description

Building X is a multi-purpose laboratory and office building. Among the many projects in progress is a long-standing study of pyro-metallurgical processes. One such project is centered in the A-Wing laboratories, and in particular room A-1. Electrorefining operations are conducted in an inert-atmosphere glove box (see Fig. 2.1-1) that has been used for many years of research using depleted uranium material and will be extended to U(20) materials. Material is passed into the glove box through a small air lock (see Fig. 2.1-2) and processed by laboratory personnel at numerous glove ports around the box.

The floor area of the glove box is approximately 2.4 m wide and 4.9 m long (8 ft x 16 ft). A cooling plenum is attached to one end of the box in which a limited amount (approximately 12 gal, held in a reservoir on the floor of the laboratory) of a water/glycol solution circulates through a heat exchanger (see Fig.2.1-3). The heat exchanger plenum contains a single fluid detector that

shuts off the liquid pump. The base of the plenum is about 18 in. x 24 in. and is 5-3/4 in. below the opening to the glove box. In addition to the coolant, only small quantities of lubricants and cleaning solutions are present in the glove box.

Figure 2.1-1. Glovebox for U(20) Operations

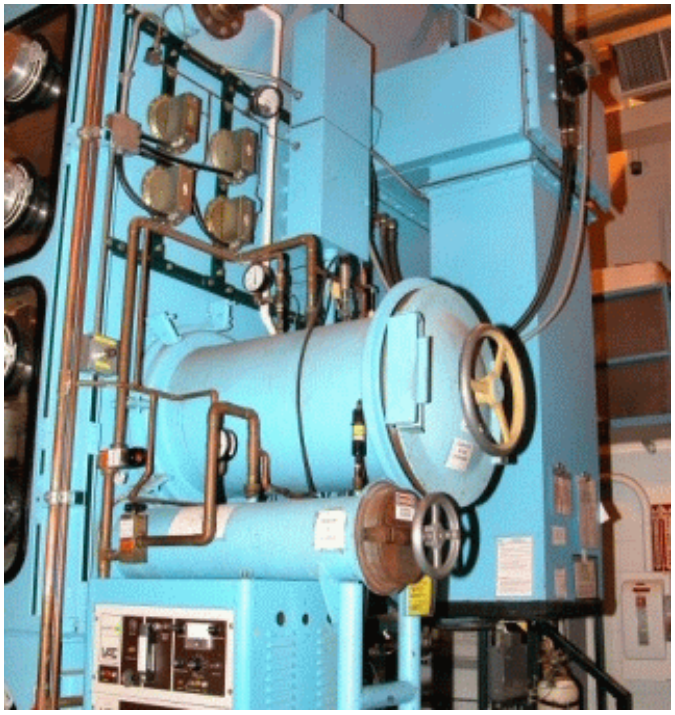

Figure 2.1-4. Glovebox Transfer Ports

Figure 2.1-3. Glovebox Atmosphere Cooling Plenum

The glove box has a heated electrorefiner well attached to the bottom of the box, with a heated flange extending about 2 cm into the box (see Fig. 2.1-4 and Fig. 2.1-5). Cooling coils surround the well, but do not enter the glove box. The cooling system contains about 12 gal of the same coolant used in the atmosphere cooling system, also held in a reservoir on the floor of the laboratory.

Figure 2.1-4. Top of Electrorefiner in Glovebox

Figure 2.1-5. Electrorefiner Vessel Below Glovebox

The electrorefiner well is a cylindrical vessel with an outer diameter of approximately 45.7 cm (18 in.) and a depth of approximately 132 cm (52 in.) that is welded to the floor of the glove box. The well is cooled by a circulating water/glycol solution system (separate from the atmosphere cooling system) that is external to the glove box. The electrorefiner crucible is 122-cm (48-in.) high with an outer diameter of 41 cm (16 in.). When the crucible assembly is inserted into the electrorefiner well, a raised flange approximately 3.5-cm high exists around the well. The electrorefiner contains a molten salt electrolyte compound that is maintained at a temperature of approximately 500 C.

The glove box is centered in the room, away from the concrete block walls. Except for the cooling system, the only other external water source in the room is the fire sprinkler system. This is not considered a potential criticality safety problem since the glove box is sealed and fire-fighting water cannot enter. Miscellaneous handling equipment and small plastic bottles are present in the glove box. The bottles contain small quantities of cleaning solutions and lubricants.

In Building X, fissile material being moved to or from other wings never enters Wing A. Facility procedures allow only one fissile material transfer in the building at a time, and the limited number of personnel who do the transfers ensures that this procedure is followed. No other nearby facilities use fissile materials, and no hazards have been identified in those facilities that could impact Building X.

2.2 Operations

The material to be used in the electro-metallurgical processing activities consists of uranium enriched to 19.7 % or 19.8 % in various forms. The material is present as uranium-silicon or uranium-silicon-aluminum compounds or mixtures. Both forms have additional minor trace elements. The end product of the electrorefining operations will be uranium metal with only minor trace elements. All operations will be performed entirely within room A-1 of Building X, with the exception of material transfers to and from the Special Materials (SPM) storage vault.

2.2.1 Material Transfer into and out of the Glove Box

Material transfers to and from the electrorefiner laboratory will be made by SPM representatives according to procedures given in the SPM Procedures Manual. According to the procedure for on-site movement of special materials, the material shall be packaged in containers similar to those used for off-site shipments. Such containers have been analyzed for criticality safety and have fissionable mass limits specific to each container type. Since only one SPM representative is responsible for material movements in the building, only one material transfer is performed at a time from storage to the electrorefiner laboratory.

It is expected that the feed stock material will be U_3Si or U_3Si-Al. As shown in the Section 6 of this evaluation, large quantities of $U_3(20)Si$ are criticality-safe as long as the material is not mixed with a moderating material. Even when mixed with water, the atomic ratio of hydrogen to ^{235}U determines the U(20) critical mass, which ranges from about 5.5 kg to many tens of kg. However, as the analysis in Section 6 shows, limiting the volume of the containers in the glove box precludes any possibility of an accidental criticality. To eliminate the possibility of a criticality accident, the feed stock material shall be transported to the electrorefiner laboratory in sealed containers (standard practice in approved shipping containers). The size of the outer transport container is limited only by SPM and container requirements. However, inner containers of material to be passed into the glove box will be limited to a maximum volume of 3.8 L (1 gal). Only two volume-limited containers will be allowed in the glove box at any one time. Although not necessary for criticality safety during normal operations, the two-container limit will preclude accidental criticality under extreme contingency situations.

2.2.2 Ancillary Glove Box Operations

Miscellaneous operations that will be performed in the glove box include weighing, material consolidation, temporary storage, transfers to and from the electrorefiner and preparation for transfer from the glove box.

As detailed in Section 6, several tens of kilograms of U(20) can be safely handled in the absence of moderating materials. By restricting the size and number of containers allowed within the glove box, even the inadvertent introduction of moderator materials will not present a criticality hazard. Within the glove box, moderating materials are restricted to the minimum amount needed for operations and most are of such a form that mixing with the fissionable

material is impossible. Moderating liquids (other than lubricants internal to equipment and the atmosphere system coolant) in the glove box are further restricted to the minimum amount necessary for an operation and are kept in closed containers when not being used. To further isolate the fissionable material in the glove box, it is also kept in closed containers when not in active use. As noted above, only two approved containers, in addition to the electrorefiner, may be open at any time during these miscellaneous operations in the glove box.

2.2.3 Electrorefiner Operations

The electrorefiner, as described in Section 2.1, contains a high-temperature molten salt into which materials containing U(20) are dissolved. Using electro-deposition techniques, metallic uranium is deposited onto a cathode in the electrorefiner. The cathode product is formed within the molten salt, then extracted and formed into a consolidated ingot during cathode processing operations.

As described in the analysis below, the molten salt in the electrorefiner acts as a diluent and neutron absorber, so that large quantities of U(20) may be present in the electrorefiner without presenting a criticality safety hazard. For operational purposes, the electrorefiner vessel is limited to a total of approximately 15 kg of U(20).

2.2.4 Cathode Product Operations

Once a cathode is collected in the electrorefiner, it will be removed and prepared for further processing. Operations on the cathode product include weighing, sampling and consolidation with other cathode product materials. Containers used to hold cathode product material are limited to a volume of 1 gal as described in the analysis results.

The cathode product is eventually melted and poured into molds which will form semi-cylindrical ingots, each with a mass of approximately 200 g. The ingots will have a radius of 1.9 cm (0.75 in.) and a length of 1.8 cm (0.72 in.) and the entire mold will have a capacity of approximately 15 kg. As discussed in Section 6, this mold is criticality-safe even when fully loaded with U(20).

Once formed, the uranium ingots will be loaded into the standard 1-gal containers and passed out of the glove box, where the material will be moved to storage or other analytical areas. Once removed from the glove box, the material is handled in the same manner as incoming feed material.

3.0 REQUIREMENTS DOCUMENTATION

Among other controlling documents, requirements for criticality safety at DOE facilities are contained in DOE Order O 420.1, [1]which incorporates by reference the ANSI/ANS-8 series of criticality safety standards. One of these requirements is that all operations with fissionable materials shall adhere to the recommendations of ANSI/ANS-8.1-1998, the base standard for

criticality safety for operations with fissionable materials outside reactors [2] including adherence to the double contingency principle, stated in both the DOE Order and ANSI/ANS-8.1.

> **Process designs shall incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions before a criticality accident is possible.** (DOE O 420.1)

Section 5 of this evaluation discusses the credible contingencies for each of the operations in the laboratory, and Section 6 presents results that document the fact that no single contingency will create conditions to allow an accidental criticality.

The recommendations in ANSI/ANS-8.1 shall be applied to operations in the electrorefiner laboratory to the extent possible, using a graded approach consistent with the amount of material in the laboratory. Written procedures, materials control, operational controls and emergency procedures shall be in effect during operation of the electrorefiner laboratory. Any change in the scope of operations shall be reviewed for potential effects on the conclusions of the criticality safety evaluation for the laboratory.

4.0 METHODOLOGY

4.1 Calculational Technique

All calculations performed in the development of this NCSE used the KENO-Va module within the SCALE 4.3 code system [3]. The executable code modules were installed directly from the CD-ROM supplied by the Radiation Safety Information Computational Center (RSICC) onto a Pentium-class computer, which was used for all calculations. Using a patch supplied by RSICC, the code was updated to the July 1996 version.

All calculations were executed under the CSAS25 control module, which invokes the BONAMI-S and NITAWL-II modules for cross section preparation. ENDF/B Version IV 27-group cross sections were used exclusively in this NCSE.

Verification of a correct installation of the code was completed by running the set of sample problems provided with the SCALE 4.3 package and confirming agreement with the reference output files.

4.2 Validation

The KENO-Va code has been extensively validated by comparison to critical experiments [4]. In addition to this and other generic validation studies that have been published, a set of validation problems has been run that relates to the specific problem being studied.

At the time this NCSE was prepared, no benchmark problems could be found for the U(20) alloys and mixtures being used in the electrorefiner glove box. However, benchmark problems

do exist for uranium at enrichments above and below 20%, so interpolation is possible and is a reliable validation technique. When unusual compounds or material forms, such as a molten salt of LiF and KF, are present, it is necessary to look at benchmark problems for similar compounds and evaluate their applicability. Several reports have been written that deal with normal and abnormal configurations that are expected in electrorefining operations [5, 6, 7, 8] although none considers the exact configuration and materials to be used in the Building X operation.

Three separate sets of conditions are identified for validation: uranium materials in a dry environment; uranium materials in a moderated, reflected environment under contingency conditions; and electrorefiner operations. Benchmark cases were taken from a report of critical experiments by Paxton [9], the subcritical limits standard reference by Clark [10] and the handbook of benchmark experiments [11].

To cover the cases of dry uranium material, benchmark calculations were made for spheres and cylinders of various enrichments, with and without reflectors, and with diluent materials present. Table 4.2-1 lists the validation case names, descriptions and results. There does not appear to be any significant bias factor for the cases presented in the table, either as a function of enrichment or as a function of material. Some cases appear to show a small bias (e.g., Case LA3067D), but because certain details were omitted from the description of some critical experiments (in this case the reflector density) the small variations from unity are not judged to be significant. Other cases, such as HEU-MF7A are calculated to be approximately 1.3% above critical, but these results agree with those presented in the reference ($k_{eff} = 1.0136 \pm 0.0015$).

To cover the contingency condition where a container of material might be flooded, several solution benchmarks were also run and are included in Table 4.2-1. The benchmark cases closest to the U(20) contingency conditions are Cases 14-16 for U(30.45) in an oxyfluoride solution. The calculated k_{eff} values for these three cases are slightly above unity, but considering the lack of detail in the reference and the large margin of subcriticality for the operations, the difference is not significant.

The third category of problems needed for validation is related to the electrorefiner, which is essentially a cylindrical vessel with molten KF and LiF and the U(20) material. Validation of the conditions present during the electrorefining operation is especially difficult because of the unique combination of materials, temperature and geometry in the system. A large number of calculations was performed in support of the criticality safety analysis for a large-scale, high-temperature electrorefiner now in operation at Argonne National Laboratory-West (ANL-W) [5, 6, 7, 8]. While the electrolyte in that system does not exactly match that in the Building X electrorefiner, it does contain many of the same isotopes. Also, that electrorefiner is designed to process highly-enriched materials. The ANL-W analysis uses the same computer code and cross sections that are used in the present analysis, and the validation studies show that both code and cross sections are adequate for the present analysis. One notable result in the ANL-W analysis is the large margin of subcriticality that exists for the normal operating mode and even for most contingency configurations. Because of a similarly large margin calculated for

the Building X electrorefiner configuration, the ANL-W validation is considered adequate to cover the system analyzed in this NCSE.

Table 4.2-1. KENO-Va Validation Calculational Results

Case No.	Case Name[a]	Description	Calculated [b] $k_{eff} \pm 1$
1	LA3067A	U(93.71) bare sphere	0.9992 ± 0.0017
2	LA3067B3	U(29.0) bare cylinder, stacked plates	1.0019 ± 0.0016
3	LA3067C	U(47.3) pseudosphere, U(N) reflector	1.0010 ± 0.0013
4	LA3067D	U(10.15) cylinder, homog., U(N) reflector	1.0030 ± 0.0011
5	LA3067E1	U(93.3) + Al, bare cylinder, homogeneous	0.9978 ± 0.0016
6	LA3067E2	U(93.3) + Al, bare cylinder, stacked plates	0.9946 ± 0.0018
7	LA3067F1	U(93.3) + Zr, bare cylinder, homogeneous	0.9992 ± 0.0016
8	LA3067F2	U(93.3) + Zr, bare cylinder, stacked plates	1.0020 ± 0.0017
9	IEU-MF2	U(16.19) cylinder, U(N) reflector, plates	0.9985 ± 0.0007
10	HEU-MF7A	HEU + teflon, bare rectangle, stacked plates	1.0135 ± 0.0015
11	HEU-ST1A	HE uranyl nitrate cylinder, bare, SS tank	1.0073 ± 0.0020
12	HEU-ST1B	HE uranyl nitrate cylinder, bare, Al tank	1.0111 ± 0.0018
13	HEU-ST9A	U(93)O_2F_2 bare solution sphere	1.0017 ± 0.0019
14	NSE81A1	U(30.45)O_2F_2 bare solution sphere, 944 g/L	1.0166 ± 0.0021
15	NSE81A2	U(30.45)O_2F_2 bare solution sphere, 81 g/L	1.0077 ± 0.0015
16	NSE81B1	U(30.45)O_2F_2 water reflected sphere, 235 g/L	1.0051 ± 0.0018

[a] Cases 1-8 from Ref. 9, LA-3067-MS; cases 9-13 from Ref. 11, NEA/NSC/DOC(95)03/I; cases 14-16 from Ref. 10, *NS&E* **81**.
[b] Results taken directly from KENO output and do not imply accuracy to four significant digits.

In summary, based on the validation results presented in Table 4.2-1 and those presented in the referenced ANL-W electrorefiner validation study, it is concluded that the KENO-Va code with ENDF/B-IV 27-group cross sections as applied in this NCSE is satisfactory for the analysis.

5.0 DISCUSSION OF CONTINGENCIES

As used in this NCSE, a contingency is defined as an unlikely event involving fissionable material that might reduce the margin to criticality for a given configuration of those materials. Note that this is a somewhat broader definition of a contingency, which is often taken to mean a situation in which the limiting value of a controlled parameter is violated. Because of the limited scope of operations in the electrorefiner glove box, only a few contingency situations are credible.

5.1 Increased Reflection of Fissionable Materials

When working in a general-purpose glove box, the possibility exists that equipment, containers or non-controlled materials may be positioned next to the fissionable material in the glove box, increasing the reactivity of the configuration. In order to account for this contingency, the evaluations presented in Section 6 generally assume a complete water reflector around containers, and a conservative amount of reflector materials elsewhere. For example, the steel plate (glove-box floor) and the concrete floor of the laboratory are both included in the model for the electrorefiner. Reflection to the extent included in the calculation is extremely unlikely (incredible in the case of full water reflection), but is shown by the analysis to be criticality safe.

5.2 Addition of Moderating Materials

As noted in Section 2, extraneous moderating materials will be kept to a minimum in the glove box. There are two potential sources of large quantities of liquid in the glove box. The first is the atmosphere cooling system, which contains a mixture of glycol and water. The second is the fire protection sprinkler system in the laboratory.

The glove box atmosphere cooling system contains approximately 45.4 L (12 gal) of a 50/50 mixture of water and glycol in a reservoir on the floor of the laboratory. This coolant is circulated by a pump through a heat exchanger which is located in a plenum attached to one end of the glove box. The plenum is designed with a sump volume below the level at which coolant could enter the main part of the glove box. The plenum internal area is approximately 45 cm (17-3/4 in.) by 60 cm (23-3/4 in.), with a height of about 14.6 cm (5-3/4 in.). Assuming all of the coolant (volume = 4.54×10^4 cm^3) leaked into this area, only about 5700 cm^3 (1.5 gal) would overflow into the glove box, forming a very thin layer. In fact, if the entire inventory of coolant were to spill into the glove box (floor area approximately 2.68×10^5 cm^2) the height of the liquid (assuming no large pieces of equipment on the floor) would only be about 0.2 cm. This amount of liquid could not credibly enter into material containers to act as a moderator, and even if it did the container limitations in the glove box preclude an accidental criticality.

The glove box is sealed to contain the inert atmosphere and to prevent release of contaminants. An inadvertent activation of the sprinkler system in the laboratory would not cause water ingress into the glove box. Similarly, a real activation of the system would cause water ingress only if the glove box were destroyed to an extent that allowed water from the

sprinklers to enter. One other combination of events that could allow water entry is an earthquake of sufficient magnitude to cause a breach in the glove box followed by activation of the sprinkler system. This combination of events has a probability that is in the extremely unlikely to incredible range.
However, since water ingress into the glove box in such a manner that it acts as both moderator and reflector cannot be categorized as incredible, the calculations presented in Section 6 include these contingency (or multiple contingency) configurations.

5.3 Inadvertent Over-batching of Containers

The nominal amount of fissionable material in the glove box at any one time is 15 kg of U(20). This limit is an operational parameter only and is not used as a criticality safety limit. The only criticality control used in the glove box is the limit of two fissionable material containers each with a volume not to exceed one gallon. Examples of such containers are the 1-gal material storage and transfer containers and the processing crucible. In addition, the electrorefiner is always allowed in the glove box. The analyses below presents the results for container overload contingencies. With the imposed container restrictions, no credible over-batching scenario results in a criticality accident.

5.4 Loss of Electrical Power

The only relevant event that might be caused by a loss of electrical power to the glove box is a reduction of the temperature of the molten salt/fuel mixture in the electrorefiner vessel. This would cause an increase in the density of the salt and eventually could lead to freezing of the salt. In the analysis of the electrorefiner, no credit was taken for the reduced density at elevated temperatures. Section 6 presents results that show the system is criticality safe in the event of salt freezing, even when additional contingencies, such as the separation of a fissionable material layer, occur.

5.5 Exceeding the Container Control Limit

One possible contingency is exceeding the number of volume-controlled containers in the glove box. This contingency will be examined in detail in the analysis section, since it represents the most probable contingency that might occur during the glove box operations. As shown by the analysis, it is possible that an array of four containers can be assembled in a critical configuration, and under certain incredible configurations even three 1-gal containers can achieve criticality. However each of these cases requires multiple contingencies, some of which have probabilities that border on the incredible. The double contingency rule is applicable to each of these situations.

6.0 EVALUATIONS AND RESULTS

6.1 U(20) Minimum Critical Mass Limits

Standard criticality safety references have little information specific to uranium enriched to 20 wt-% ^{235}U. Most information deals with low enriched systems (less than 5 wt-% ^{235}U) or highly enriched systems at 93 wt-% ^{235}U. No information on U_3Si or U_3Si-Al materials is readily available. As a result of this lack of specific information, a series of calculations was performed to define the minimum critical mass for various combinations of U(20) mixed with water and U_3Si mixed with water, with and without a water reflector. These results are compared to the few data available from other sources. [*Note: since this NCSE was written, additional U(20) validation data have been made available.*]

Paxton and Pruvost [12] give the following minimum critical mass values for bare and water moderated U(20) spheres.

. 160 kg(^{235}U)	metal, unreflected (graph page 43)
. 1.9 kg(^{235}U)	water moderated, unreflected (graph page 52)
. 1.1 kg(^{235}U)	water moderated, water reflected (graph page 52)

The Nuclear Safety Guide [13] gives a value of 20.1 kg (Table 2.2) as the subcritical mass limit for dry ^{235}U (water reflected) at a density of 18.8 g/cm^3, and a subcritical limit for general (i.e., not solutions) ^{235}U-water mixtures (page 24) of 700 g(^{235}U). Note that in the context of this reference, the subcritical limit is lower than the actual minimum critical mass. To account for lower-enrichment material, the Guide allows the mass of the U-water mixture to be increased by a factor of 6.4 for U(20) (graph page 74). It allows the mass of the reflected metal sphere to be increased by a factor of 15.5 (graph page 73). With these factors, the Guide yields the following subcritical mass limits for U(20).

. 62 kg(^{235}U)	metal, water reflected
. 0.9 kg(^{235}U)	water moderated, water reflected

To supplement these data points from the handbooks, a series of KENO-Va calculations were made to determine the minimum critical mass values for mixtures of U(20) and water. Table 6.1-1 shows the results of the calculations for reflected and unreflected spheres of material. All calculations assumed a uranium density of 19.05 g/cm^3 and a water density of 0.9982 g/cm^3 (KENO default values). Figure 6.1-1 graphically shows the variation of the minimum critical mass of U(20) as a function of the moderator to fissile ratio (H:^{235}U).

Table 6.1-2 shows a comparison of the data points from References 12 and 13 with the KENO calculations. The KENO values for the water-moderated systems are estimates from Fig. 6.1-1. The results from the three sources are consistent, considering the graphical estimation required for enrichment factors and the difference between critical mass and a subcritical mass limit.

Table 6.1-1. KENO-Va Critical Mass Results for U(20)-Water Mixtures				
Volume Fraction U(20)	No Reflector		Water Reflector (30 cm)	
	Case Name	Critical Mass kg(U)	Case Name	Critical Mass kg(U)
1.0	U20W0BS	773	U20W0WS	327
0.15	U20W5BS	64.2	U20W5WS	28.8
0.1	U20W2BS	40.8	U20W2WS	17.5
0.07	U20W4BS	28.0	U20W4WS	12.3
0.05	U20W1BS	20.1	U20W1WS	9.16
0.03	U20W3BS	17.0	U20W3WS	8.08
0.02	U20W7BS	10.3	U20W7WS	5.39
0.013	U20W11BS	11.9	U20W11WS	5.10
0.01	U20W6BS	8.78	U20W6WS	5.28
0.008	U20W8BS	9.75	U20W8WS	6.35
0.006	U20W9BS	12.9	U20W9WS	9.62
0.004	U20W10BS	67.9	U20W10WS	48.6

Table 6.1-2. Comparison of Critical Mass Data for U(20)			
	Critical Mass, kg(U)		
	LA-10860-MS	TID-7016 Rev. 2 [a]	KENO Calculation
Metal No Reflector	800	---	773
Metal Water Reflector	---	310	327
Water Moderator No Reflector	9.5	---	8.8
Water Moderator Water Reflector	5.5	4.5	5.0
[a] Subcritical mass limit values.			

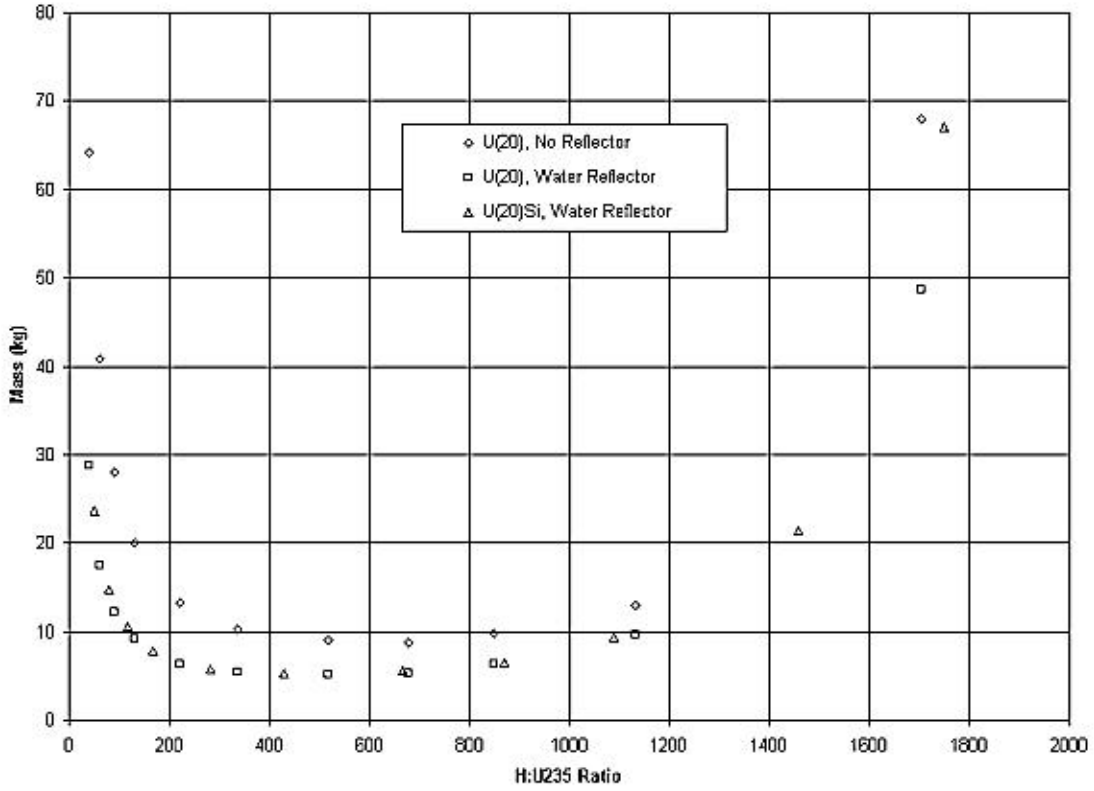

Figure 6.1-1. Minimum U(20) and U_3(20)Si Critical Mass vs Moderator Content

Since one of the main materials to be processed in Room A-1 is U_3Si, a similar parametric evaluation was done for that material. Since the exact form and density of the material to be processed has not been determined, a theoretical density of 15.4 g/cm^3 was assumed for the calculations. Following the same approach used to generate the U(20) critical mass data, a series of KENO calculations was performed to determine the minimum critical mass of $U(20)_3Si$ as a function of the moderator-to-fissile ratio for water-reflected spheres. Table 6.1-3 shows the results of the calculations for water-reflected spheres of this material. This data is included in Fig. 6.1-1. The minimum critical mass for a $U(20)_3Si$-water system is slightly larger than the U(20)-water system, and occurs at a higher volume fraction of uranium material. It is clear from the curves that outside of a narrow H:^{235}U ratio range of about 200 to 1100 the critical masses of both materials increase rapidly. The direct conclusion of these parametric studies is that if the material containing U(20) can be kept dry, it will present no criticality hazard in the quantities present for processing in Building X.

Table 6.1-3. KENO-Va Critical Mass Results for $U(20)_3Si$-Water Mixtures		
Volume Fraction $U_3(20)Si$	Water Reflector (30 cm)	
	Case Name	Critical Mass kg(U)
1.0	U20T10WS	467
0.15	U20T5WS	23.7
0.1	U20T2WS	14.7
0.07	U20T4WS	10.5
0.05	U20T1WS	7.89
0.03	U20T3WS	5.76
0.02	U20T7WS	5.30
0.013	U20T11WS	5.55
0.01	U20T6WS	6.48
0.008	U20T8WS	9.33
0.006	U20T9WS	21.4
0.005	U20T10WS	67.0

6.2 Transfer and Storage Containers

From an operational point of view, material transfers should be made with a batch size that does not unnecessarily increase the number of transfers, yet ensures criticality safety even if contingencies occur. For the limited scale of operations in the J-Wing electrorefiner laboratory, it has been determined that a transfer batch size of 10 kg of U(20) is operationally acceptable.

At a nominal uranium theoretical density of 19.05 g/cm^3, a 10-kg batch of U(20) would only require a container volume of 525 cm^3, making a 1-L can a suitable candidate. It was shown in Section 6.1 that the minimum critical mass of U(20) is highly dependent on the ratio of fissile to moderator atoms. Using the volume of the can and the densities of U(20) and water, it is possible to create a curve of U(20) mass vs the moderator to fissile ratio and compare the results to the parametric curves presented in Section 6.1. Figure 6.2-1 shows the results of such calculations for 1-L, 2-L and 1-gal cans (each with a height-to-diameter ratio of 1.0, a higher reactivity geometry than that of the actual cans). These curves show that restricting the volume of the material transfer containers (e.g., to 1-gal) precludes the possibility of a criticality event. Figure 6.2-2 shows a similar set of curves for $U(20)_3Si$.

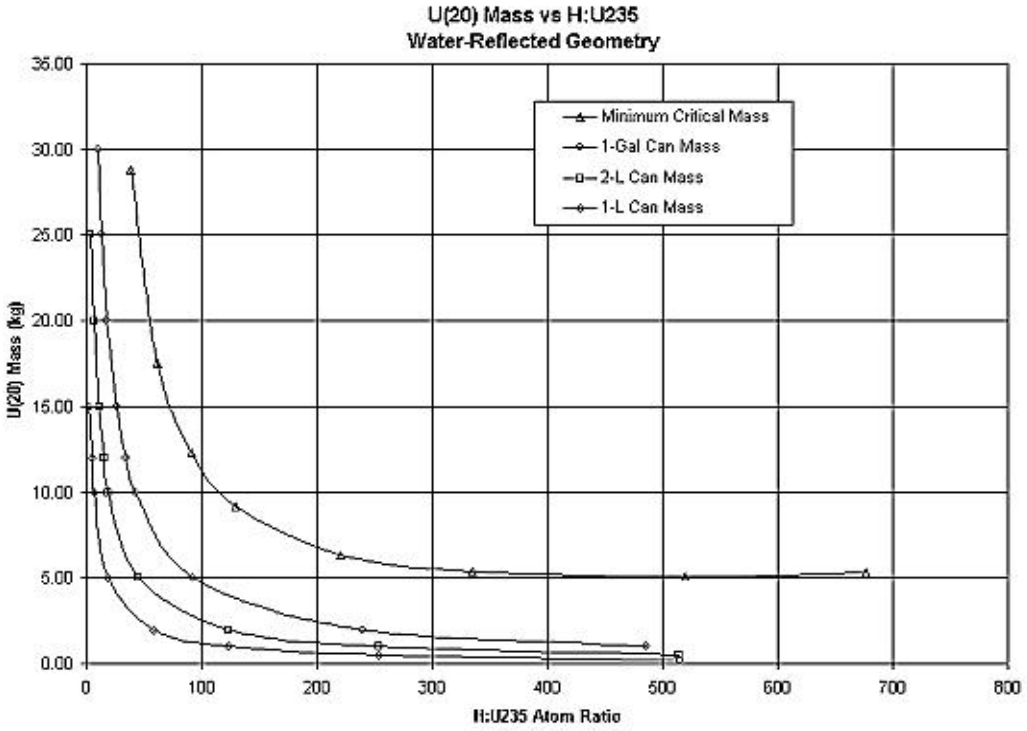

Figure 6.2-1. Comparison of Container Capacities with U(20) Minimum Critical Mass

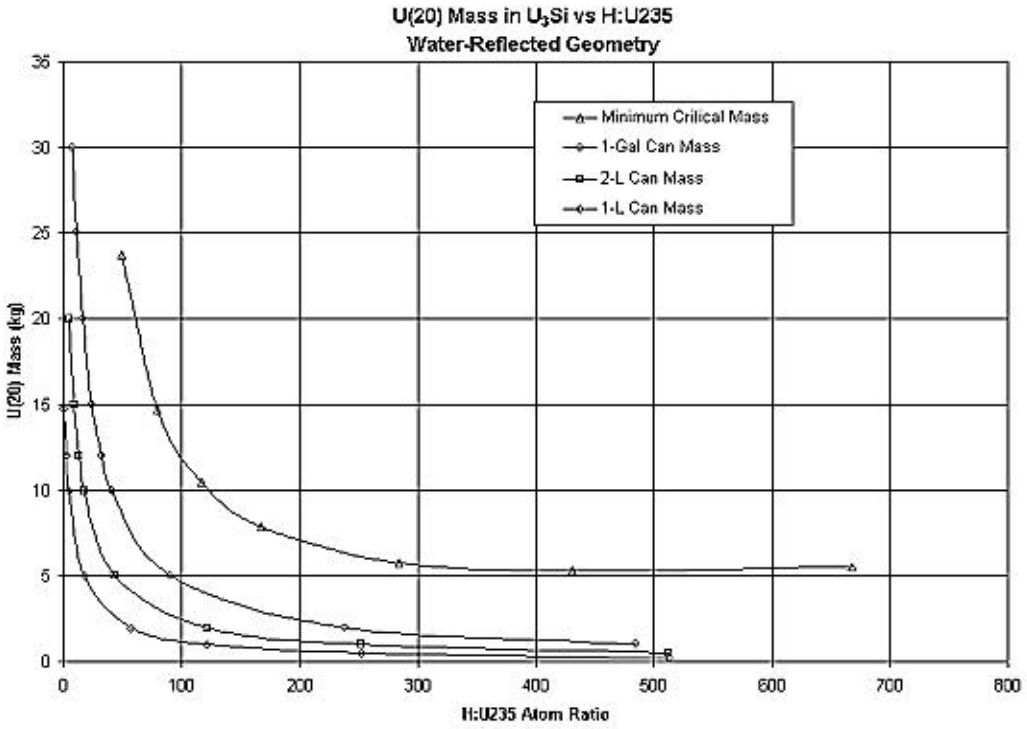

Figure 6.2-2. Comparison of Can Capacities with U_3(20)Si Minimum Critical Mass

For example, if a container holds 10 kg of U(20), Fig. 6.2-1 indicates it would require the H:^{235}U ratio to be about 125 to achieve a critical mass. However, filling even a 1-gal can with water would only raise the ratio to about 40, for which the critical mass of U(20) is above 25 kg. The curves clearly show that for any given U(20) mass content, it is impossible to achieve a critical configuration in a single can, even assuming an essentially infinitely-thick water reflector.

By restricting the volume of containers (other than the electrorefiner) to 1 gal, they can be used to move feed stock materials into the glove box as well as move the U(20) cathode product out of the glove box while maintaining criticality safety, even if the operational mass limit is increased above the nominal 10 kg value.

To verify the results described above based on the parametric studies, a series of KENO calculations was performed for a 1-gal can with a height-to-diameter ratio of 1.0 surrounded by 30 cm of water on all sides containing various amounts of U(20) and water. Table 6.2-1 shows the results of the calculations which are shown graphically in Figure 6.2-3.

Table 6.2-1 KENO-Va Calculations for U(20) Water Mixtures in 1-gal Can

Case Name	U(20) Volume Fraction	U(20) Mass (kg)	H : ^{235}U	k_{eff}
U20GAL01	1.0	72.1	0	0.7686 ± 0.0014
U20GAL02	0.5	36.1	7	0.7819 ± 0.0017
U20GAL03	0.15	10.8	39	0.8100 ± 0.0020
U20GAL04	0.1	7.2	62	0.8120 ± 0.0019
U20GAL05	0.05	3.6	130	0.7939 ± 0.0021
U20GAL06	0.01	0.72	677	0.5988 ± 0.0015
U20GAL07	0.005	0.36	1360	0.4466 ± 0.0011

One contingency considered in Section 5 is the inadvertent introduction of more that two of the standard volume-controlled containers. To analyze this situation, a series of calculations was performed with arrays of 1-gal containers. The calculations were repeated with two-, three- and four-container arrays with various gap sizes between the containers and with both metal and a metal-water mixture in the containers. The additional contingency of water flooding was included in some of the models.

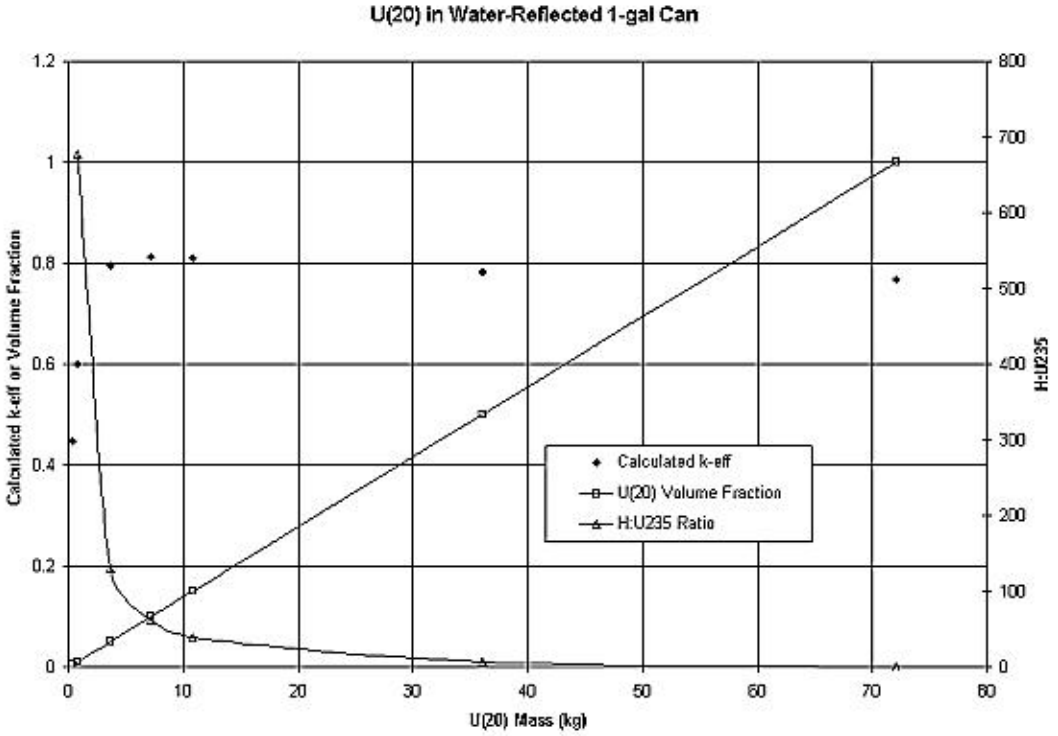

Figure 6.2-3. Calculated k-eff of Reflected 1-gal Container of Moderated U(20)

The basic array model consists of the containers on top of a 1.9-cm thick steel plate with a water reflector. In the most conservative model, a water-metal mixture was assumed with water reflector on the sides and top of the containers. The second model used the water-metal mixture but eliminated the water reflector on top of the containers . The third series of calculations assumed each container was filled with full-density U(20) with water reflector on the sides. Table 6.2-2 shows the results of these three series of calculations.

These results show that two containers are criticality safe in the glove box, even assuming a worst-case flood contingency. Adding an extra container (first contingency) does not appreciably reduce the margin to criticality except under extreme flooding conditions (second contingency) and even then the system is subcritical. Only when two extra containers are brought into the glove box and a flooded condition is assume (three contingencies) is there a possibility for a criticality. This situation is judged to be incredible and is beyond the requirements of the double contingency principle.

Table 6.2-2. Calculated k_{eff} Values for Arrays of 1-gal Containers				
Case Name [a]	Gap (cm)	1 x 2 Array	1 x 3 Array	2 x 2 Array
U20GnnB1	0.0	0.8894 ± 0.0030	0.9870 ± 0.0029	1.0129 ± 0.0029
U20GnnB2	0.5	0.8854 ± 0.0024	0.9757 ± 0.0029	1.0029 ± 0.0028
U20GnnB3	1.0	0.8812 ± 0.0033	0.9757 ± 0.0028	0.9879 ± 0.0024
U20GnnB4	4.0	0.8373 ± 0.0029	0.9377 ± 0.0028	0.9076 ± 0.0028
U20GnnC1	0.0	0.8185 ± 0.0030	0.9004 ± 0.0028	0.9324 ± 0.0028
U20GnnC2	0.5	0.8191 ± 0.0029	0.9020 ± 0.0029	0.9227 ± 0.0028
U20GnnC3	1.0	0.8128 ± 0.0027	0.8989 ± 0.0031	0.9099 ± 0.0032
U20GnnC4	4.0	0.7724 ± 0.0029	0.8653 ± 0.0032	0.8390 ± 0.0028
U20GnnD1	0.0	0.7600 ± 0.0021	0.8240 ± 0.0023	0.8734 ± 0.0022
U20GnnD2	0.5	0.7645 ± 0.0023	0.8375 ± 0.0021	0.8712 ± 0.0020
U20GnnD3	1.0	0.7574 ± 0.0022	0.8492 ± 0.0023	0.8727 ± 0.0020
U20GnnD4	4.0	0.7430 ± 0.0020	0.8374 ± 0.0021	0.8149 ± 0.0020
[a] nn=02 for 1x2 array cases, =03 for 1x3 array cases, =04 for 2x2 array cases; cases 'B' include full water reflection of containers with 10 vol-% U(20) and 90 vol-% water; cases 'C' include side water reflection, vacuum above containers and the same water-U(20) mixture as 'B'; cases 'D' include side water reflection, vacuum above containers and full-density metal in the containers.				

6.3 Electrorefiner Operations

While the exact composition of the electrorefiner salt and the final dimensions of the system have yet to be determined, a series of scoping calculations was performed to look for any potential criticality safety problems with the electrorefiner operations. The cylindrical vessel is assumed to be steel, with an outer diameter of 40.64 cm and a total height (including top plate) of 136.3 cm. The bottom of the vessel is directly above a 61-cm (24-in.) thick concrete floor and suspended below a steel plate. The height of the salt is taken to be 61 cm (24 in) with a diameter of 38 cm. For some calculations a cylindrical cathode was placed in the salt with an assumed diameter of 20.32 cm (8 in) and a height of 25.4 cm (10 in). The bottom of the cathode was placed 33 cm above the bottom of the salt pool. Calculations were made with uranium volume fractions of 0.1 and 0.2 in the cathode region, with salt occupying the remaining volume.

The molten salt mixture was assumed to be 50 wt-% each of LiF and KF, with 10 kg of U(20) present as UF_3. The assumed densities for these materials are: (LiF) = 2.635 g/cm^3, (KF) = 2.48 g/cm^3, (UF_3) = 7.5 g/cm^3. Calculations were made with all materials at 293 K, increasing the densities above those to be expected at the normal operating temperature.

Table 6.3-1 shows the results of the KENO-Va k_{eff} calculations for both a nominal loading with and without a cathode, plus several increased-mass cases. It is clear that the electrorefiner assembly is far subcritical for even highly improbable loadings.

Table 6.3-1. KENO-Va Calculated k_{eff} Values for Simulated Electrorefiner			
Case Name	U(20) in Salt (kg)	U(20) in Cathode (kg)	Calculated k_{eff}
U-ER01A	10	0	0.0244 ± 0.0002
U-ER02A	10	15.7	0.1395 ± 0.0008
U-ER02B	10	31	0.2430 ± 0.0012
U-ER02C	20	31	0.2580 ± 0.0013

6.4 Cathode Processing Operations

Cathode processing (CP) operations include a broad range of activities involving the output product of the electrorefiner operations, such as consolidation of multiple cathodes, casting batch preparation and melting the cathode product into ingots for eventual casting. CP operations are also restricted by the container limit imposed on all glove box operations. However, in addition to the standard polyethylene storage containers, a crucible is present during these operations. The final composition and design of the crucible has yet to be determined, but for this preliminary NCSE it is assumed to be a 2-cm thick hemisphere made of carbon.

The inner diameter of the crucible is 16.0 cm, giving it a capacity of 20.4 kg(U). The base model consists of the carbon crucible upright on top of a 1.9-cm thick carbon steel plate. Contingency configurations include an inverted crucible, water reflection on the sides of the crucible and water reflection on the top and sides of the crucible. One calculation was also done using a uranium-water mix (U volume fraction about 0.12). Table 6.4-1 shows the results of the crucible calculations. Even for a completely filled (at the uranium theoretical density) crucible with extremely unlikely configurations, the assembly is far subcritical.

6.5 Casting Operations

The final product of the operations in the electrorefiner laboratory will be cast ingots of refined uranium. After melting the cathode product in a casting crucible, the molten material will be poured into a mold that holds approximately 15 kg of U(20). Based on a preliminary design, the casting mold is modeled as a graphite block 25.4 cm (10 in.) long, 27 cm (10-5/8 in.) wide and 3.81 cm (1.5 in.) deep. Cut into the top surface of this block are six semi-cylindrical cavities with a radius of 1.905 cm (0.75 in) and a length of 22.86 cm (9.0 in.) to hold the uranium. The axes of these cutouts are separated by 4.13 cm (1-5/8 in.) and are 1.27 cm (0.5 in) from the edge of the block. The carbon block is mounted on a base plate of carbon steel 1.27-cm (0.5-in.) thick.

Table 6.4-1. KENO-Va Calculated Results for Generic Crucible Configurations		
Case Name	Description	k_{eff}
CRUC-1A	Upright on steel plate, no water reflection	0.3374 ± 0.0012
CRUCW1A	Upright on steel plate, water reflector on sides only	0.4030 ± 0.0014
CRUCW1B	Upright on steel plate, water reflector on sides and top	0.5593 ± 0.0021
CRUC-2A	Inverted on steel plate, no water reflection	0.3481 ± 0.0012
CRUCW2A	Inverted on steel plate, water reflector on sides only	0.4111 ± 0.0015
CRUCW2B	Inverted on steel plate, water reflector on sides and top	0.4707 ± 0.0015
CRUCW1C	Upright on steel plate, water reflector on sides and top, U plus water mixture	0.5399 ± 0.0026

Calculations were made for the nominal case (no reflection) as well as for partially- and fully-reflected configurations. Each of these models contains 14.9 kg of solid U(20) and is far subcritical as shown by the results given in Table 6.5-1.

Table 6.5-1. KENO-Va Calculated Results for Casting Mold Configurations		
Case Name	Description	k_{eff}
CAST01B	Bare block, no reflection	0.1390 ± 0.0013
CAST02A	Water reflection on four sides of block	0.1465 ± 0.0013
CAST02B	Water reflection on sides and top of block	0.4289 ± 0.0033

7.0 OPERATING LIMITS AND CONTROLS

The following criticality safety rules apply to operations in Room A-1 of Building X.

1. The only fissile material allowed in Room A-1 is uranium enriched to 20% or less in 235U.

2. Only one fissile material transfer operation into or out of Room A-1 may be in progress at any time. Simultaneous transfers are not allowed.

3. With the exception of the electrorefiner vessel, only containers with a volume of 1 gal (3.8 L) or less are allowed in the glove box in Room A-1.

4. A maximum of two fissile material containers in addition to the electrorefiner are allowed in the glove box in Room A-1.

In addition to these rules, operators are expected to follow good laboratory practices such as keeping containers closed when not in use and minimizing the amount of moderator materials in the glove box.

8.0 SUMMARY

The results presented in this preliminary NCSE have shown that all planned operations in the electrorefiner glove box can be performed in a criticality-safe manner. Furthermore, the results show that these operations remain criticality-safe even when multiple contingencies occur, demonstrating the fact that the double contingency principle is rigorously followed during operations in this facility.

9.0 REFERENCES

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3. "SCALE 4.3: Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation for Workstations and Personal Computers," RSIC Computer Code Collection CCC-545 (October 1995).

4. W. C. Jordan, N. F. Landers and L. M. Petrie, "Validation of KENO V.a Comparison with Critical Experiments," Oak Ridge National Laboratory Report ORNL/CSD/TM-238 (December 1986).

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6. R. M. Lell, "Validation of KENO V.a and the Standard Composition Library for HFEF/S Modifications Criticality Analysis Part II," Argonne National Laboratory IFR Document F5130-0008-EK, Rev. 0 (April 12, 1993).

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9. H. C. Paxton, "Los Alamos Critical-Mass Data," Los Alamos National Laboratory Report LA-3067-MS (December 1975).

10. H. K. Clark, "Subcritical Limits for Uranium-235 Systems," *Nuclear Science and Engineering*, **81**, 351-378 (1982).

11. "International Handbook of Evaluated Criticality Safety Benchmark Experiments," Nuclear Energy Agency Publication NEA/NSC/DOC(95)03/I (1995).

12. H. C. Paxton and N. L. Pruvost, "Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu, and ^{233}U, 1986 Revision," Los Alamos National Laboratory Report LA-10860-MS (July 1987).

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10.0 SAMPLE KENO INPUT LISTINGS

Sample input listing for the various models and configurations discussed in the text are presented here. Complete input and output listings of all cases discussed in the text are available upon request.

```
#CSAS4
U20W2BS: SPHERE, H2O + 20% ENR URANIUM, 27-GR ENDF/B-IV, K-EFF SEARCH
27GROUPNDF4          INFHOMMEDIUM
URANIUM  1  0.1   293.  92235  20.  92238  80.  END
H2O      1  0.9   293.  END
H2O      2  1.0  293.  END
END COMP
SPHERE, H2O + 20% ENR URANIUM REFERENCE SEARCH
READ PARM TME=100 TBA=30 RUN=YES PLT=NO END PARM
READ GEOM
SPHERE  1  1  15.0
CUBE    0  1  6P40.0
END GEOM
READ ARRAY
GBL=1  ARA=1 NUX=1 NUY=1 NUZ=1  FILL 1  END FILL
END ARRAY
READ BNDS
ALL=VACUUM
END BNDS
END DATA
READ SEARCH
CRITICAL DIMENSION EPS=0.005   MORE
MODIFY  UNIT=1  REG=1  R=1.0  +CON=0.4  -CON=-0.7
END SEARCH
END
```

```
#CSAS4
U20T2WS: WATER REFL SPHERE, 20% ENR U3SI+H2O, 27-GR ENDF/B-IV, K-SEARCH
27GROUPNDF4          INFHOMMEDIUM
ARBM-U3SI  15.4  2 1 1 1  92000 3  14000 1
         1  0.1  293.  92235  20.  92238  80.  END
H2O      1  0.9  293.  END
H2O      2  1.0  293.  END
END COMP
WATER REFL SPHERE, 20% ENR FULL DENSITY U3SI K-EFF SEARCH
READ PARM TME=100 TBA=30 RUN=YES PLT=NO END PARM
READ GEOM
SPHERE  1  1  13.0
SPHERE  2  1  43.0
CUBE    0  1  6P60.0
END GEOM
READ ARRAY
GBL=1  ARA=1 NUX=1 NUY=1 NUZ=1  FILL 1  END FILL
END ARRAY
READ BNDS
ALL=VACUUM
END BNDS
END DATA
```

```
READ SEARCH
CRITICAL DIMENSION EPS=0.005   MORE
MODIFY  UNIT=1  REG=1  R=1.0  +CON=0.3  -CON=-0.3
MAINTAIN UNIT=1  REG=2  ALL=1.0
END SEARCH
END
```

```
#CSAS25
U20GAL04: H2O + 20% ENR U IN 1 GAL POLY CAN, H2O REFLECTOR
27GROUPNDF4          INFHOMMEDIUM
URANIUM   1  0.1  293.  92235  20.  92238  80.  END
H2O       1  0.9  293.  END
H2O       2  1.0  293.  END
POLY(H2O) 3  1.0  293.  END
END COMP
1 GAL POLY CAN, H2O + 20% ENR FULL DENSITY U, H2O REFLECTOR
READ PARM TME=100 TBA=30 RUN=YES PLT=NO FLX=YES
     GEN=215 NPG=1000 NSK=15 END PARM
READ GEOM
CYLINDER  1  1  8.44586 8.44586 -8.44586
CYLINDER  3  1  8.64586 8.64586 -8.64586
CYLINDER  2  1  38.64586 38.64586 -38.64586
CUBE  0  1  6P40.0
END GEOM
READ ARRAY
GBL=1  ARA=1 NUX=1 NUY=1 NUZ=1  FILL 1  END FILL
END ARRAY
READ BNDS
ALL=VACUUM
END BNDS
END DATA
END
```

```
#CSAS25
LA3067B3: U(29.0) BARE STACKED CYLINDER, LA-3067 P5
27GROUPNDF4          MULTI
URANIUM  1  DEN=18.787 1.0  293.  92235  93.4  92238  6.6  END
URANIUM  2  DEN=18.787 1.0  293.  END
END COMP
SLAB VACUUM VACUUM 0 END
     1  0.8  2  2.60  END ZONE
BARE U(29.0) CYLINDER, HETEROGENEOUS MODEL, RHO=18.787 G/CC
READ PARM TME=100 TBA=30 RUN=YES PLT=NO FLX=YES
GEN=240  NPG=1000  NSK=40  END PARM
READ GEOM
UNIT 1
COM='0.6 CM U(N) PLATE AT BASE OF STACK'
CYLINDER  2  1  14.5034 0.6 0.0
CUBOID    0  1  14.5034 -14.5034 14.5034 -14.5034 0.6 0.
UNIT 2
COM='0.8 CM U(93.4) PLATES'
CYLINDER  1  1  14.5034 0.8 0.0
CUBOID    0  1  14.5034 -14.5034 14.5034 -14.5034 0.8 0.
UNIT 3
COM='1.8 CM U(N) PLATES'
CYLINDER  2  1  14.5034 1.8 0.0
CUBOID    0  1  14.5034 -14.5034 14.5034 -14.5034 1.8 0.
```

```
UNIT 4
COM='PARTIAL U(93.4) AT TOP OF STACK'
CYLINDER  1  1  14.5034 0.026767 0.0
CUBOID    0  1  14.5034 -14.5034 14.5034 -14.5034 0.026767 0.
UNIT 5
COM='PARTIAL U(N) AT TOP OF STACK'
CYLINDER  2  1  14.5034 1.536234 0.0
CUBOID    0  1  14.5034 -14.5034 14.5034 -14.5034 1.536234 0.
END GEOM
READ ARRAY
GBL=1  ARA=1 NUX=1 NUY=1 NUZ=28
FILL 1 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 3 2 4 5  END FILL
END ARRAY
READ BNDS
ALL=VACUUM
END BNDS
END DATA
END
```

```
#CSAS25
IEU-MF2: U(16.19) CYLINDER, 27-GR ENDF/B-IV, IEU-MET-FAST-002
27GROUPNDF4          INFHOMMEDIUM
U-234  1  0.0 8.4430E-5  END
U-235  1  0.0 7.7777E-3  END
U-238  1  0.0 3.9671E-2  END
U-234  2  0.0 2.6433E-6  END
U-235  2  0.0 3.4603E-4  END
U-238  2  0.0 4.7711E-2  END
END COMP
U REFLECTED U(16.19) CYLINDER, HOMOGENEOUS MODEL, RHO=18.75
READ PARM TME=100 TBA=30 RUN=YES PLT=NO FLX=YES
GEN=305 NPG=2000 NSK=5 END PARM
READ GEOM
CYLINDER  1  1  19.05 39.571 7.62
CYLINDER  2  1  26.6446 47.0894 0.
END GEOM
END DATA
END
```

```
#CSAS25
U20G02B1: 1X2 ARRAY, H2O+20% ENR U IN 1 GAL POLY CAN, H2O REFLECTOR
27GROUPNDF4          INFHOMMEDIUM
URANIUM   1  0.1  293.  92235  20.  92238  80.  END
H2O       1  0.9  293.  END
H2O       2  1.0  293.  END
POLY(H2O) 3  1.0  293.  END
CARBONSTEEL  4  1.0  293.  END
END COMP
1 GAL POLY CAN, H2O + 20% ENR FULL DENSITY U, H2O/STEEL REFLECTOR
READ PARM TME=100 TBA=30 RUN=YES PLT=NO FLX=YES
     GEN=115 NPG=1000 NSK=15 END PARM
READ GEOM
UNIT 1
CYLINDER  1  1  8.45 8.45 -8.45
CYLINDER  3  1  8.65 8.65 -8.65
UNIT 2
COM=!BOUNDING CYLINDER OF WATER WITH STEEL PLATE BOTTOM!
```

```
CYLINDER  2  1   47.3  38.65  -8.65
HOLE      1     -8.65   0.0    0.0
HOLE      1      8.65   0.0    0.0
CYLINDER  4  1   47.3  38.65  -10.56
CUBE      0  1  6P48.0
END GEOM
READ ARRAY
GBL=1  ARA=1 NUX=1 NUY=1 NUZ=1  FILL 2  END FILL
END ARRAY
READ BNDS
ALL=VACUUM
END BNDS
READ PLOT
TTL=!EBWR CONTROL ROD FOLLOWERS!
PLT=YES PIC=MIXTURE XUL=0 YUL=100 ZUL=48 XLR=100 YLR=0 ZLR=48
  UAX=1 VAX=0 WAX=0 UDN=0 VDN=-1 WDN=0 NAX=80 END
END PLOT
END DATA
END
```

```
#CSAS25
U20G03B1: 1X3 ARRAY, H2O+20% ENR U IN 1 GAL POLY CAN, H2O/STEEL REFL
27GROUPNDF4          INFHOMMEDIUM
URANIUM   1  0.1  293.  92235  20.  92238  80.  END
H2O       1  0.9  293.  END
H2O       2  1.0  293.  END
POLY(H2O) 3  1.0  293.  END
CARBONSTEEL  4  1.0  293.  END
END COMP
1 GAL POLY CAN, H2O + 20% ENR FULL DENSITY U, H2O/STEEL REFLECTOR
READ PARM TME=100 TBA=30 RUN=YES PLT=NO FLX=YES
     GEN=115 NPG=1000 NSK=15 END PARM
READ GEOM
UNIT 1
CYLINDER  1  1  8.45 8.45 -8.45
CYLINDER  3  1  8.65 8.65 -8.65
UNIT 2
COM=!BOUNDING CYLINDER OF WATER WITH STEEL PLATE BOTTOM!
CYLINDER  2  1   48.64  38.65  -8.65
HOLE      1      0.0   9.98816    0.0
HOLE      1     -8.65   -4.99408    0.0
HOLE      1      8.65   -4.99408    0.0
CYLINDER  4  1   48.64  38.65  -10.56
CUBE      0  1  6P49.0
END GEOM
READ ARRAY
GBL=1  ARA=1 NUX=1 NUY=1 NUZ=1  FILL 2  END FILL
END ARRAY
READ BNDS
ALL=VACUUM
END BNDS
READ PLOT
TTL=!3-CONTAINER ARRAY!
PLT=NO PIC=MIXTURE XUL=0 YUL=100 ZUL=49 XLR=100 YLR=0 ZLR=49
  UAX=1 VAX=0 WAX=0 UDN=0 VDN=-1 WDN=0 NAX=80 END
END PLOT
END DATA
END
```

```
#CSAS25
U20G04B1: 2X2 ARRAY, H2O + 20% ENR U IN 1 GAL POLY CAN, H2O/STEEL REFL
27GROUPNDF4          INFHOMMEDIUM
URANIUM   1  0.1  293.  92235  20.  92238  80.  END
H2O       1  0.9  293.  END
H2O       2  1.0  293.  END
POLY(H2O) 3  1.0  293.  END
CARBONSTEEL  4  1.0  293.  END
END COMP
1 GAL POLY CAN, H2O + 20% ENR FULL DENSITY U, H2O REFLECTOR
READ PARM TME=100 TBA=30 RUN=YES PLT=NO FLX=YES
     GEN=115 NPG=1000 NSK=15 END PARM
READ GEOM
UNIT 1
CYLINDER  1  1  8.45 8.45 -8.45
CYLINDER  3  1  8.65 8.65 -8.65
UNIT 2
COM=!BOUNDING CYLINDER OF WATER WITH STEEL BASE!
CYLINDER  2  1  50.883  38.65  -8.65
HOLE      1     -8.65   8.65   0.0
HOLE      1      8.65   8.65   0.0
HOLE      1      8.65  -8.65   0.0
HOLE      1     -8.65  -8.65   0.0
CYLINDER  4  1  50.883  38.65  -10.56
CUBE   0  1  6P51.0
END GEOM
READ ARRAY
GBL=1  ARA=1 NUX=1 NUY=1 NUZ=1  FILL 2  END FILL
END ARRAY
READ BNDS
ALL=VACUUM
END BNDS
END DATA
END
```

```
#CSAS25
U-ER02B: 10 KG 20% ENR UF3 IN KF+LIF ER, 30 KG U CATHODE
27GROUPNDF4          INFHOMMEDIUM
ARBM-KF  2.48  2 0 1 0  19000 1  9019 1
         1  0.5028965  293.  END
ARBM-LIF 2.635 2 1 1 0  3000 1  9019 1
         1  0.4733143  293.  END
ARBM-UF3 7.50  2 1 1 1  92000 1  9019 3
         1  0.0237892  293.  92235  20.  92238  80.  END
CARBONSTEEL  2  1.0  293.  END
ARBM-KF  2.48  2 0 1 0  19000 1  9019 1
         3  0.4023172  293.  END
ARBM-LIF 2.635 2 1 1 0  3000 1  9019 1
         3  0.37865144  293.  END
ARBM-UF3 7.50  2 1 1 1  92000 1  9019 3
         3  0.01903136  293.  92235  20.  92238  80.  END
URANIUM  3  0.20  293.  92235  20.  92238  80.  END
END COMP
J118 ELECTROREFINER, 20% ENR UF3 IN KF+LIF WITH 30 KG CATHODE
READ PARM TME=100 TBA=30 RUN=YES PLT=YES END PARM
READ GEOM
UNIT 1
```

```
CYLINDER  3  1  10.16  58.4   33.0
CYLINDER  1  1  19.05  62.405  0.0
CYLINDER  0  1  19.05  132.0  0.0
CYLINDER  2  1  20.32  135.0  -1.27
CUBOID    0  1  4P20.32 135.0  -1.27
END GEOM
READ ARRAY
GBL=1  ARA=1  NUX=1  NUY=1  NUZ=1  FILL 1 END FILL
END ARRAY
READ BNDS
XFC=VACUUM  YFC=VACUUM  +ZB=VACUUM  -ZB=CONC24
END BNDS
READ PLOT
PLT=YES  SCR=NO  PIC=MIX  XUL=0.0  XLR=41.0  YUL=41.  YLR=0.
ZUL=35.  ZLR=35. UAX=1 VAX=0 WAX=0 UDN=0 VDN=-1 WDN=0
DLX=.4  LPI=8  END
PLT=YES  SCR=NO  PIC=MIX  XUL=0.0  XLR=41.0  YUL=20.32.  YLR=20.32
ZUL=137.  ZLR=0. UAX=1 VAX=0 WAX=0 UDN=0 VDN=0 WDN=-1
DLX=.4  LPI=8  END
END PLOT
END DATA
END
```

```
#CSAS25
CRUCW1A: 20 KG U(20) IN HEMISPHERE GRAPHITE CRUCIBLE, WATER REFL
27GROUPNDF4          INFHOMMEDIUM
URANIUM      1  1.0  293.  92235  20.  92238  80.  END
C            2  1.0  293.  END
CARBONSTEEL  3  1.0  293.  END
H2O          4  1.0  293.  END
END COMP
J118 CASTING CRUCIBLE, 20 KG CAPACITY, 8.0 CM ID HEMISPHERE
READ PARM TME=100 TBA=30 RUN=YES  PLT=NO  FLX=YES
     GEN=115  NPG=1000  NSK=15  END PARM
READ GEOM
UNIT 1
COM='BOUNDING CYLINDER FOR CRUCIBLE AND STEEL BASE'
HEMISPHE-Z  1  1  8.0
HEMISPHE-Z  2  1  10.0
CYLINDER    4  1  40.0  0.0  -10.0
CYLINDER    3  1  40.0  0.0  -11.9
CUBOID      0  1  45.0  -45.0  45.0  -45.0  5.0  -12.0
END GEOM
READ ARRAY
GBL=1  ARA=1 NUX=1 NUY=1 NUZ=1  FILL 1  END FILL
END ARRAY
READ BNDS
ALL=VACUUM
END BNDS
READ PLOT
PLT=YES  SCR=YES  PIC=MIX  XUL=0.  XLR=90.  YUL=45.0  YLR=45.0
ZUL=12.  ZLR=0. UAX=1 VAX=0 WAX=0 UDN=0 VDN=0 WDN=-1
NDN=600  NAX=600  LPI=10  END
PLT=YES  SCR=YES  PIC=MIX  XUL=0.  XLR=90.  YUL=90.  YLR=0.
ZUL=11.8  ZLR=11.8  UAX=1 VAX=0 WAX=0 UDN=0 VDN=-1 WDN=0
NDN=600  NAX=600  LPI=10  END
END PLOT
END DATA
```

```
END
```

```
#CSAS25
CAST02B: U(20) IN GRAPHITE MOLD, SEMI-CYL PIECES, 5-SIDE WATER REFL
27GROUPNDF4          INFHOMMEDIUM
URANIUM      1  1.0  293.  92235  20.  92238  80.  END
C            2  1.0  293.  END
CARBONSTEEL  3  1.0  293.  END
H2O          4  1.0  293.  END
END COMP
J118 CASTING MOLD, 15 KG CAPACITY, 10 X 10-5/8 X 1-1/2 IN., REFLECTED
READ PARM TME=100 TBA=30 RUN=YES  PLT=NO  END PARM
READ GEOM
UNIT 1
COM='SEMI-CYLINDRICAL MOLD, 1.5 IN. OD, 9 IN. LONG, ORIGEN AT BOTTOM'
YHEMICYL-Z  1  1  1.905  22.86  0.0
UNIT 2
COM='BOUNDING BOX FOR MOLD, WATER REFLECTOR AND STEEL BASE'
CUBOID  2  1  26.9875  0.0  25.4  0.0  0.0  -3.81
HOLE    1  3.175    1.27  0.0
HOLE    1  7.3025   1.27  0.0
HOLE    1  11.43    1.27  0.0
HOLE    1  15.5575  1.27  0.0
HOLE    1  19.685   1.27  0.0
HOLE    1  23.8125  1.27  0.0
CUBOID  3  1  26.9875  0.0  25.4  0.0  0.0  -5.08
CUBOID  4  1  56.9875  -30.0  55.4  -30.0  30.0  -5.08
CUBOID  3  1  56.9875  -30.0  55.4  -30.0  30.0  -7.08
END GEOM
READ ARRAY
GBL=1  ARA=1 NUX=1 NUY=1 NUZ=1  FILL 2  END FILL
END ARRAY
READ BNDS
ALL=VACUUM
END BNDS
READ PLOT
PLT=YES  SCR=YES  PIC=MIX  XUL=0.0  XLR=90.0  YUL=40.0  YLR=40.0
ZUL=40.0  ZLR=0.0 UAX=1 VAX=0 WAX=0 UDN=0 VDN=0 WDN=-1
NDN=600  NAX=600  LPI=10  END
PLT=YES  SCR=YES  PIC=MIX  XUL=0.0  XLR=90.0  YUL=90.0  YLR=0.0
ZUL=7.05  ZLR=7.05 UAX=1 VAX=0 WAX=0 UDN=0 VDN=-1 WDN=0
NDN=600  NAX=600  LPI=10  END
END PLOT
END DATA
END
```